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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE Jan. 15, 1992		3. REPORT TYPE AND DATES COVERED Final Technical 15Nov 86 - 14 Dec 91	
4. TITLE AND SUBTITLE (U) Studies in Turbulence and Turbulence Control				5. FUNDING NUMBERS PE - 61102F PR - 2307 SA - RS G - AFOSR 87-0116	
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NA Building 410 Bolling AFB DC 20332-6448				10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFOSR- 87-0116	
11. SUPPLEMENTARY NOTES Final Report					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Projects studied under this AFOSR grant are summarized. They concern the following aspects, and are believed to be of interest for both applications and fundamentals of fluid mechanics and aerospace sciences: (1) Flow Control, (2) Chaos and universality in wakes behind circular cylinders, (3) Absolute instability and the dynamics of variable density jets, (4) Kinematics and dynamics of turbulent vorticity fluctuations in laboratory and atmospheric turbulence, and (5) Fractals and multifractals in fluid flows. The report lists the Ph.D. theses and principal publications arising from the work. Reprints of some of the important papers are attached. The report also contains a section on the impact of the research. A list of Ph.D. students funded at least partly from the grant is given.					
14. SUBJECT TERMS Turbulence, Turbulence Control, chaos, universality, vorticity, LEBU, Combustion instability, variable density jets, Fractals, Multifractals				15. NUMBER OF PAGES 160	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL		

FINAL REPORT FOR THE GRANT AFOSR-87-0116

Studies in Turbulence and Turbulence Control

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DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
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I. Summary of the work

The principal aspects of the work completed under the sponsorship of this grant are summarized below. Details can be found in the various Ph.D. theses and publications listed at appropriate places. Several minor aspects of the work appeared as abstracts in various places, but these are not listed here.

1. Flow Control

A. Mechanisms of possible drag reduction due to the so-called large-eddy break-up devices (LEBUs)

In continuation of the previous effort towards understanding the manner in which the boundary layer large eddy manipulators work, Garelick examined in his Ph.D thesis the effect of introducing the manipulators in laminar flows. The work was motivated by a previous hypothesis of the PI that the lift on the manipulator device was important in bringing about the drag reduction attributed to the device. A boundary layer analysis showed that a net drag reduction may be achieved by a lifting manipulator with sufficiently large lift-to-drag ratio, but a more detailed numerical analysis of the Navier-Stokes equations at significantly lower Reynolds numbers did not support the conclusion. A possible conclusion is that the drag reduction can be attained only at high Reynolds numbers.

Principal document: Numerical analysis of manipulated laminar flows, and the effect of periodic forcing at the leading edge of an airfoil at angles-of-attack near stall, Ph.D. thesis by M.S. Garelick, 1988

B. Effect of periodic forcing at the leading edge of an airfoil at angles-of-attack near stall

A preliminary effort was also made by Garelick to understand the benefits of unsteady forcing at the leading edge of an airfoil near stall. Forcing was accomplished by a rotor mounted near the leading edge. For some test conditions, periodic forcing reduced the extent of upper surface separation, but the effects were not large enough to warrant the application of the scheme, say, as a high lift device.

Principal document: Garelick's thesis cited above.

C. Suppression of combustion instability (and other fluid dynamic instabilities)

The previous work on combustion instability, carried out also by AFOSR support, was written up as the Ph.D thesis of S. Raghu (who is now assistant professor of mechanical engineering at SUNY, Stony Brook, NY). An AIAA paper was written up during the term of this grant, and was presented at an AIAA meeting. Briefly, the work consists of the development of a theory for controlling a general

disturbance field. The theory yields some broad means of accomplishing control. These theoretical ideas were tested in experimental situations both in the laboratory and in a large combustion tunnel at WPAFB, Ohio.

Principal publication: Control of acoustically coupled combustion and fluid dynamic instabilities by S. Raghu & K.R. Sreenivasan, AIAA paper 87-2690, 1987

2. Chaos and universality in wakes behind circular cylinders

In his Ph.D. thesis, Olinger examined more carefully the work initiated by the PI on the question of the applicability of low-dimensional chaos and universality to the early stages of transition in the wake behind a circular cylinder. He established that the precise nature of bifurcation corresponding to the onset of vortex shedding is of the Hopf type. He then examined the effect of factors such as aspect ratio and cylinder vibrations on the subsequent evolution to quasiperiodicity and chaos. The dynamics of the oscillating cylinder was studied experimentally and compared with the universal predictions of the circle map. This correspondence was studied from dynamical as well as statistical point of view. First steps were made in establishing the connection between the observed universality and the equations of motion by deriving a circle map from the Landau-Stuart equation.

Olinger also studied another fluid system, namely the dripping capillary jet, in which he found connections with circle map dynamics.

Principal documents: (a) Universality in the transition to chaos in open fluid flows, Ph.D thesis by D.J. Olinger, 1990; (b) Nonlinear dynamics of the wake of an oscillating cylinder by D.J. Olinger & K.R. Sreenivasan, Phys. Rev. Lett. 60, 797-800, 1988

3. Absolute instability and the dynamics of variable density jets

A study was made of the instability and subsequent breakdown of non-buoyant axisymmetric jet of helium/air mixtures in various proportions. It was established that the primary control parameters which determined the nature of instability were: (a) the ratio of the density of the nozzle gas to that of the ambient gas, and (b) the ratio of the nozzle diameter to the momentum thickness of the shear layer at the nozzle exit. For a certain range of values in the plane of these two parameters, intense oscillatory instability develops. The connection of this instability to the absolute instability was examined in detail by comparing experimental results with theoretical results. An attempt was also made to explain this instability in physical terms. The project was motivated by its possible connection to flames.

Principal documents: (a) Absolute instability in variable density round jets by K.R. Sreenivasan, S. Raghu & D.Kyle, Experiments in Fluids, 7, 309-317, 1989; (b) The instability and breakdown of round variable-density jets, Ph. D. thesis by D.M. Kyle, 1991; (c) The instability and breakdown of variable-density jets, to appear in J. Fluid Mech.

4. Kinematics and dynamics of turbulent vorticity fluctuations in laboratory and atmospheric turbulence

Measurements of the longitudinal component of vorticity were made both in laboratory flows and the atmosphere. Statistical aspects such as spectra, probability densities, multifractal spectra were obtained, and several interesting conclusions on their Reynolds number variation were made. For example, the probability density functions are more or less Gaussian-like at low Reynolds numbers but exponential-like at high Reynolds numbers. The meaning of these changes was examined. Also examined was the fractal structure of the vorticity interface.

Principal documents: (a) Features of vorticity in fully turbulent flows, Ph.D. thesis by M.S. Fan, 1990; (b) Joint multifractals: Theory and applications to turbulence by C. Meneveau, K.R. Sreenivasan, P. Kailasnath & M.S. Fan, Phys. Rev. A. 41, 894-913, 1990

5. Fractals and multifractals in fluid flows

Further work on the fractal dimension of scalar interfaces was carried out theoretically and experimentally. Work was continued on the multifractal nature of the turbulent energy dissipation as well as scalar dissipation, and other intermittent aspects of turbulence (such as the Reynolds stress). The work was carried out at very fundamental as well as experimental or empirical level. Basic issues such as singularities of the equations of motion, connection to thermodynamic formalism, cascade models were explored. Practical problems such as mixing and intermittency were studied. New theoretical results were obtained for multivariate multifractal measures. The results of this work have since been used for developing closed form expressions for the probability density functions of the velocity differences.

It is a little early to tell whether this work will have lasting consequences, but it has already had some impact on further development of the field of turbulence.

Principal publications:

1. Dynamics of countercurrent mixing layers Ph.D. thesis by R. Ramshankar, 1988
2. Multifractal nature of turbulence Ph.D. thesis by C. Meneveau, 1989
3. Singularities of the equations of fluid motion by K.R. Sreenivasan & C. Meneveau, Phys. Rev. A. 38, 6287-6295, 1988
4. New results on the fractal and multifractal structure of the large Schmidt number passive scalars in fully turbulent flows by K.R. Sreenivasan, Physica D 38, 322-329, 1989
5. Extraction of underlying multiplicative process from multifractals via the thermodynamic formalism by A.B. Chhabra, R.V. Jensen & K.R. Sreenivasan, Phys. Rev. A. 40, 4593-4611, 1989
6. Mixing, entrainment and fractal dimension of interfaces in turbulent flows by K.R. Sreenivasan, R. Ramshankar & C. Meneveau, Proc. Roy. Soc. A. 421, 79-108, 1989

8. The measurement and interpretation of fractal dimensions of the scalar interface in turbulent flows by R.R. Prasad & K.R. Sreenivasan, Phys. Fluids A 2, 792-807, 1990
9. Interface dimension in intermittent turbulence by C. Meneveau & K.R. Sreenivasan, Phys. Rev. A. 41, 2246-2248, 1990
10. Fractals and multifractals in fluid turbulence by K.R. Sreenivasan, 23, 539-600, 1991
11. The multifractal nature of turbulent energy dissipation by C. Meneveau & K.R. Sreenivasan, J. Fluid Mech. 224, 429-484, 1991

II. Ph.D. students whose graduate work was partly supported by this grant

Note: Most of the people listed below received significant part of their support from this AFOSR grant during their graduate studies at Yale. After graduation, they have gone on to do various things without necessarily perpetuating in detail the work they did here.

1. Melvin Garelick is an assistant professor of engineering at the U.S. Merchant Marine Academy, Kings Point, NY, and teaches fluid mechanics and thermodynamics
2. Ram Ramshankar is a research engineer at the Carrier Corporation, Syracuse, NY, and works on air conditioning and fluid flow problems involving heat transfer
3. Charles Meneveau is an assistant professor of mechanical engineering at Johns Hopkins University, Baltimore, MD, and teaches fluid mechanics and does research in turbulence
4. David Olinger is an assistant professor of mechanical engineering at Worcester Polytechnic Institute, Worcester, MA, and teaches fluid mechanics and does research in aerodynamics
5. Mark Fan is a research engineer in NASA at Greenbelt, MD, and works on aspects of the space program
6. David Kyle is a research engineer at Oak Ridge National Laboratories, Oak Ridge, TN, and is working on new energy systems and related issues

III. The impact of research work completed under the grant

Our work on the LEBUs, even though unpublished by and large, has had some effect on the subsequent direction pursued by others. For instance, Dennis Bushnell of NASA Langley was an external reader for Mel Garelick's thesis; at least partly through him, the work has penetrated other circles.

The work on combustion instability has had much more direct impact. My graduate student at the time (Dr. S. Raghu) spent a summer at the Wright Patterson Air Force Base with Dr. Roquemore's group and worked with their combustion tunnel. By using some of the techniques developed in our

laboratory, Raghu was successful in suppressing the combustion instability in the Wright Patterson facility.

The work on the universality in the wake has had a somewhat ambiguous beginning. My first work got involved in an unnecessary controversy which has since been resolved, I believe, in my favor by the work of Charles Williamson (now at Cornell). Our subsequent work has received a lot of attention in many communities outside of fluid mechanics. I rarely exaggerate, and I hope I am right in stating that when this gets written up eventually, it will become an important contribution for a long time to come.

The work on absolute instability was begun with application to flames in mind. We have not made this connection directly, but the possibilities have become clearer. For example, I have been in touch with Dr. Roquemore of Wright Patterson Air Force Base in trying to replicate some of their observations in flames by means of a suitably simulated helium air jets. I have at one time given some lectures at Wright Patterson on this topic, and intend to pursue this connection further. At another level, this work has fed other work that got done elsewhere in heated jets.

The vorticity work has not been published much, but it may have had some influence any way. For instance, I have been told by Professor Victor Yakhot at Princeton that in all his talks he presents our data and makes comparison with his theory.

The work on fractals and multifractals has opened up several new lines of inquiry both by us and by others subsequently. All of it has not yet been digested, and it is difficult to predict the permanent impact on turbulence, but there is no question that it has already penetrated different lines of research and thinking to different degrees.

All in all, even in my most honest and self-critical moments, I feel good about the work that was done, and I am thankful to AFOSR for making some of it possible. I have included some reprints for more details but, unfortunately, not all were available at this time. The final word on the influence of the work is through the people it helped train. As Section II shows, this is pretty good.